

# Measuring the extragalactic background light from very high energy gamma-ray observations of blazars

Qiang Yuan<sup>1</sup>, Hai-Liang Huang<sup>1,2</sup>, Xiao-Jun Bi<sup>1</sup>, and Hong-Hao Zhang<sup>2</sup>

<sup>1</sup>*Key Laboratory of Particle Astrophysics,  
Institute of High Energy Physics,  
Chinese Academy of Sciences,  
Beijing 100049, P. R. China*

and

<sup>2</sup>*School of Physics and Engineering, Sun Yat-Sen University, Guangzhou 510275, P. R. China  
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The extragalactic background light (EBL) contains important information about stellar and galaxy evolution. It leaves imprint on the very high energy  $\gamma$ -ray spectra from sources at cosmological distances due to the process of pair production. In this work we propose to *measure* the EBL directly by extracting the collective attenuation effects in a number of  $\gamma$ -ray sources at different redshifts. Using a Markov Chain Monte Carlo fitting method, the EBL intensities and the intrinsic spectral parameters of  $\gamma$ -ray sources are derived simultaneously. No prior shape of EBL is assumed in the fit. With this method, we can for the first time to derive the spectral shape of the EBL model-independently. Our result shows the expected features predicted by the present EBL models and thus support the understanding of the EBL origin.

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The extragalactic background light (EBL) is the diffuse radiation from ultraviolet to far infrared wavelengths, spread isotropically in the universe (for a review of EBL, see [1, 2]). The EBL originates from the radiative energy releases of all the stars, other extragalactic sources and diffuse emissions since the epoch of recombination. Therefore its intensity and spectral shape hold crucial information about the formation and evolution of stellar objects and galaxies throughout the cosmic history. The EBL is one of the fundamental quantities in cosmology.

Direct measurement of EBL is, however, very difficult due to the contamination of the foreground emission from the solar system zodiacal light and the Galactic stellar and interstellar emissions [3]. Technically, it also requires the absolute calibration of the instruments, and the understanding all measurement uncertainties. Given the difficulties, direct measurements provide just lower and upper limits of EBL intensity. A strict lower limit on the EBL intensity is provided by the integrated light from resolved galaxies, e.g. in optical by the Hubble Space Telescope [4] and in infrared by the Spitzer telescope [5]. The upper limit can be derived from the absolute measurement of EBL within its errors [1]. The allowed range is shown by the shadow region in the following figures.

Extreme efforts had been paid to calculate the EBL intensity [6–12]. The models generally include two distinctive processes, that the UV and optical component of EBL is the integral of starlight over all epochs and the infrared component is due to the process of absorp-

tion and re-emission of starlight by the interstellar dust. These models agree on the overall EBL shape, including two maxima at  $\sim 1\mu\text{m}$  by starlight and at  $\sim 100\mu\text{m}$  by dust. However, since the detailed EBL model depends on many factors, such as the star formation history, the stellar initial mass function, the evolution of metallicity, the energy released by AGN, the size distribution and composition of dust grains, different models keep a large diversity.

There is another indirect but effective way to study the EBL by observation of very high energy (VHE)  $\gamma$ -rays. The VHE  $\gamma$ -rays from extragalactic sources are attenuated by the process of electron/positron pair production,  $\gamma_{\text{VHE}} + \gamma_{\text{EBL}} \rightarrow e^+e^-$ , when propagating to the Earth (e.g., [13–15]). With the rapid development of ground based  $\gamma$ -ray imaging atmospheric Cerenkov telescopes (IACT), quite a few VHE  $\gamma$ -ray sources from cosmological distances have been detected, most of which are blazars, a subgroup of active galactic nuclei (AGN), with relativistic jet pointing towards the observer. With assumption of the intrinsic blazar spectra we can set an upper limit of the EBL intensity by comparing the observed spectra with the intrinsic spectra [15]. The observations of blazars H 2356-309 and 1ES 1101-232 at redshifts  $z = 0.165$  and  $z = 0.186$  respectively by HESS has set a strong upper limit of EBL, close to the lower limit set by galaxy counts, at the near infrared wavelength [16]. The MAGIC observation of 3C 279 at  $z = 0.536$  set upper limit at the optical band [17]. In [18] Mazin and

Raue gave a comprehensive study of EBL based on eleven blazars over a redshift range from 0.03 – 0.18. They explored a large number of hypothetical EBL scenarios and set robust constraints on EBL over a wide wave-length range. With the Fermi observation of blazar spectra at GeV to  $\sim 100$  GeV more stringent constraints on EBL are recently given by [19–24]. Those studies seem to indicate that the Universe is more transparent than we had expected.

The power of this method to study EBL is limited due to the fact that the intrinsic spectrum of each blazar is unknown. Therefore it is hard to disentangle the absorption effect by EBL from the intrinsic emission nature for a specific observation. The usual practice in the literature is to reconstruct the blazar intrinsic spectrum from the observation by first assuming an EBL model. The EBL model is rejected if it results in an unphysical intrinsic spectrum, for example, the reconstructed intrinsic spectrum follows a power law with an extremely hard spectral slope or even shows an exponential rise at the high energy end. Recently with large sample of  $\gamma$ -ray blazars, the EBL intensities were derived through a likelihood fit with given spectral template of the EBL [25, 26].

Considering the quickly accumulating number of  $\gamma$ -ray sources observed by IACTs and Fermi, which will be improved essentially by the future Cerenkov telescope array (CTA) [27–29], we propose to *measure* the EBL directly by extracting the collective absorption effects in a number of  $\gamma$ -ray sources at different redshifts. In this work we demonstrate the capability of this method by adopting the Markov Chain Monte Carlo (MCMC) fitting to known data to extract the parameters of the intrinsic spectra of a series of TeV blazars, as well as the EBL intensities simultaneously. Different from the previous studies in the literature, we make no assumption of the EBL model in our fitting. Instead the EBL is divided into many discrete energy bins and the energy density in each bin is fitted as a free parameter  $\xi_i$ .

The observed VHE  $\gamma$ -ray spectrum after absorption by the EBL is commonly expressed as

$$F_{\text{obs}}(E) = e^{-\tau(E,z)} F_{\text{int}}(E), \quad (1)$$

where  $F_{\text{int}}(E)$  is the intrinsic spectrum of the source at redshift  $z$ . The strength of the attenuation by EBL is described by the optical depth  $\tau(E, z)$  as a function of energy  $E$  and the source redshift  $z$ . The optical depth  $\tau$

is expressed as [30]

$$\tau(E, z) = \int_0^z dl(z') \int_{-1}^{+1} d\mu \frac{1-\mu}{2} \cdot \int_{\epsilon'_{\text{thr}}}^{\infty} d\epsilon' n'(\epsilon', z') \sigma(E', \epsilon', \mu), \quad (2)$$

where variables with prime are the quantities at redshift  $z'$ ,  $dl = c dt = \frac{c}{H_0} \frac{dz'}{(1+z')\sqrt{\Omega_M(1+z')^3 + \Omega_\Lambda}}$  is the differential path traveled by the VHE photon,  $\mu = \cos \theta$  with  $\theta$  the angle between the momenta of VHE and EBL photons,  $n'(\epsilon', z') = n(\epsilon'/(1+z'), z=0)(1+z')^3$  is the EBL number density at redshift  $z'$ , and  $\sigma$  is the pair production cross section.  $\epsilon'_{\text{thr}}$  is the threshold energy for  $\gamma$ -ray energy  $E' = E(1+z')$  with an angle  $\cos \theta = \mu$  with the EBL photon. The cross section is peaked at a wavelength  $\lambda/\mu\text{m} \sim 1.24E/\text{TeV}$  [31]. Therefore the observation of VHE  $\gamma$ -ray spectra can probe EBL at the wavelength from optical to far infrared, while it is not sensitive to UV band. The cosmological parameters used in this work are  $\Omega_M = 0.274$ ,  $\Omega_\Lambda = 1 - \Omega_M$ ,  $H_0 = 70.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [32].

In the fitting the intrinsic spectra of blazars  $F_{\text{int}}$  are parameterized by a power-law ( $F \propto E^{-\alpha}$ ) or log-parabolic ( $F \propto E^{-\alpha-\beta \log E}$ ) function, with two or three free parameters for each source. The blazar spectrum is usually explained by the synchrotron-self-Compton (SSC) model, which shows a concave  $\gamma$ -ray spectrum. Such a spectrum can be formulated by the log-parabolic function. If the measured energy range is not too wide the simple power-law can give a quite good description. In the following we will compare the results with the two spectral forms.

No prior assumption about EBL shape is adopted in this study. The EBL intensities are divided into 10 bins logarithmically between 0.1 and 100  $\mu\text{m}$ . Within each bin the intensity  $\nu I_\nu$  is assumed to be a constant  $\xi_i$ . Then we can fit the 10  $\xi_i$ s, according to Eq. (1), from a set of observed  $\gamma$ -ray spectra  $F_{\text{obs}}(E)$ .

We have adopted seven blazars in this study, which have relatively precise spectral measurements. The sources adopted are listed in Table I. Since the redshifts of these sources are less than 0.2, we neglect the evolution of the EBL [16].

We employ the MCMC algorithm to do this global fit, which is very efficient for the minimization in high-dimensional parameter space [40]. Physical constraints on the parameters are adopted. In models of diffusive shock acceleration of electrons in the blazar jets the deduced  $\gamma$ -ray spectra are strongly constrained with power law index  $\alpha$  larger than 1.5 [41]. The parameter  $\beta$  is restricted in  $[0, 1]$ , and we shall test in the following that

TABLE I: Source sample information

Name	redshift	Experiment	Reference
Mkn 421	0.031	VERITAS	[33]
Mkn 501	0.034	HEGRA	[34]
1ES 1959+650	0.047	HEGRA	[35]
PKS 2005-489	0.071	HESS	[36]
PKS 2155-304	0.116	HESS	[37]
H 2356-309	0.165	HESS	[38]
1ES 1101-232	0.186	HESS	[16]

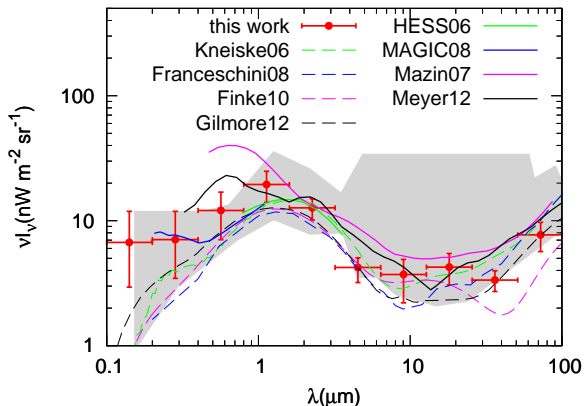


FIG. 1: The best-fitting results of the EBL intensities in 10 wavelength bins. The intrinsic spectra of blazars are assumed to be log-parabolic and the low state of Mkn 421 spectrum by VERITAS is adopted. The solid lines show the upper limits derived by the  $\gamma$ -ray observations of blazars, HESS06 [16], Mazin07 [18], MAGIC08 [17], and Meyer12 [24], and the dashed lines show the model predictions of Kneiske06 [39], Franceschini08 [6], Finkel10 [7] and Gilmore12 [8].

relaxing the range of  $\beta$  does not change the results significantly. The EBL intensities  $\xi_i$  are restricted in the lower and upper limits set by direct measurements [1].

Fig. 1 shows the fitting result assuming log-parabolic intrinsic spectra of blazars. There are seven states of Mkn 421 observed by VERITAS [33], and the low state spectrum (sample 2 as defined below) is adopted in this fit due to its wide energy coverage. For comparison, several recent model predictions of the EBL at  $z = 0$  [6–8, 39] are plotted by the dashed lines in the figure. Our fitting result agrees very well with the model predictions for  $\lambda > 1 \mu\text{m}$ . The expected peaks at  $\sim 1 \mu\text{m}$  and  $\sim 100 \mu\text{m}$  are also shown in this model-independent fit. It is very interesting that the indirect *measurement* of EBL provides strong support to the present understanding of EBL origin. The solid lines in the same plot show several current upper bounds on the EBL intensities according to the  $\gamma$ -ray observations of blazars [16–18, 24].

In the following we discuss the robustness of the method. The largest uncertainty comes from the unknown nature of the source emission. Fortunately Mkn 421 provides a perfect template to test the method. The observations by VERITAS of Mkn 421 covered seven states from very low to very high states from 2006 to 2008 [33]. We can test the convergence of EBL by the fitting procedure using the different states data at the same source. Fig. 2 shows the results by combining the other 6 sources with the different states of Mkn 421 (referred as sample 1-7 from very low to very high state), for assumption of power-law (left) and log-parabolic (right) intrinsic spectra of the sources. For power-law intrinsic spectra, the results show moderate diversity among different data set, while for the log-parabolic intrinsic spectra the results converge quite well.

The reduced  $\chi_r^2 = \chi^2/\text{d.o.f.}$  are listed in Table II. It is shown that for power-law source spectra the reduced  $\chi_r^2$  varies for different data samples. In most of these cases the  $\chi^2$  values are too large. For the log-parabolic source spectra, the reduced  $\chi_r^2 \sim 1$  for almost all of the data samples. This means the SSC model predicted log-parabolic function can give a quite well description to the intrinsic  $\gamma$ -ray spectra. For Mkn 421, some of the seven observations span the energy range for more than 1.5 orders of magnitude [33], thus the simple power-law is not a good description.

Then we relax our constraints on the parameter space. The EBL intensities are relaxed to be within  $[1, 100] \text{ nW m}^{-2} \text{ sr}^{-1}$ . The spectral parameters are relaxed as  $\alpha \geq 2/3$ ,  $0 \leq \beta \leq 2$  respectively. The results are shown in Fig. 3. We notice that the current adopted data sample can not constrain the EBL with  $\lambda < 1 \mu\text{m}$ . The UV-optical band can be constrained by sources at high redshift and lower energy, such as the 3C 279 at  $z = 0.536$  [17]. However, since only 5 points of 3C 279 was given by MAGIC it has no help to improve the fit because to include it we need to introduce 3 additional source parameters.

In summary we propose to *measure* the EBL from the VHE  $\gamma$ -ray data by a global fitting method. Both the intrinsic spectral parameters and the EBL intensities are fitted simultaneously using an MCMC algorithm, without any assumption of the spectral shape of EBL. With a log-parabolic VHE  $\gamma$ -ray spectra the fitting shows well convergence for the EBL intensities. The EBL intensities are close to the lower bound of EBL set by galaxy counts and are consistent with the recent EBL models. With the greatly improved number of VHE  $\gamma$ -ray sources by the future CTA the EBL can be determined with much higher precision.

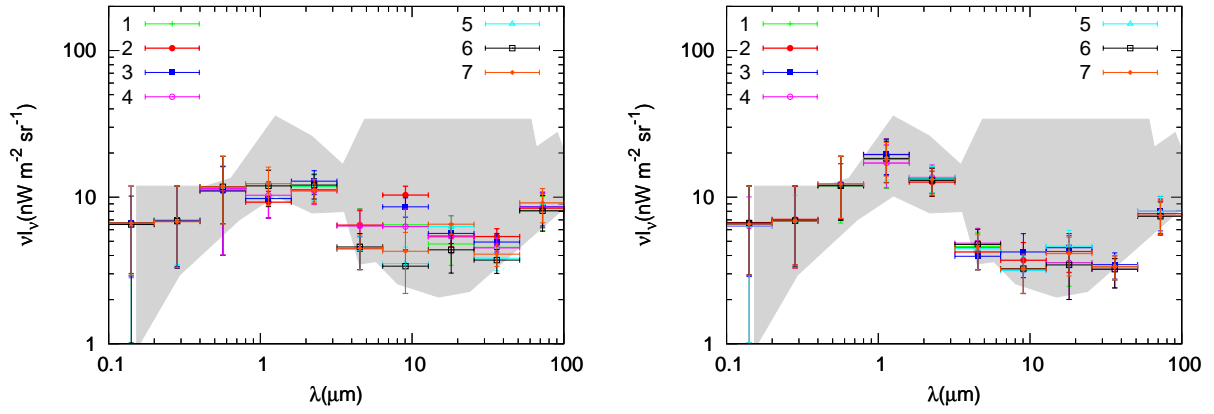


FIG. 2: The best-fitting results of the EBL intensities in 10 wavelength bins, for the assumptions of power-law (left) and log-parabolic (right) intrinsic spectra of the sources. Different symbols are for different data sets (see the text for details).

TABLE II: Best-fit  $\chi^2/\text{d.o.f.}$  values

	1	2	3	4	5	6	7
power-law	90.8/55	89.4/58	73.6/59	87.6/56	64.7/50	46.8/50	63.4/53
log-parabolic	54.7/48	60.2/51	61.8/52	53.1/49	61.2/43	46.1/43	52.9/46

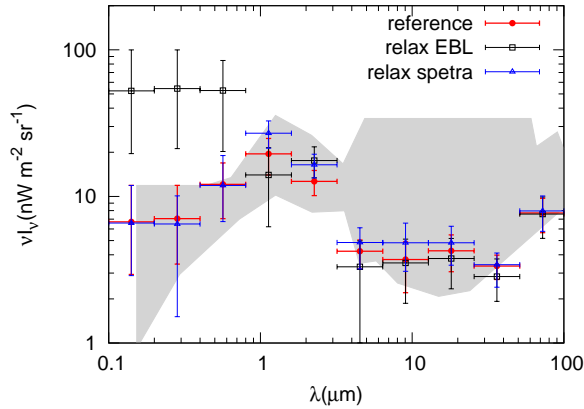


FIG. 3: Comparison of the results for relaxing fitting ranges of the EBL intensities or the spectral parameters. The reference case is the log-parabolic fit to data sample 2.

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